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Accelerated Corrosion In Weathering Steel Bridges

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Abstract:

Weathering steel has been used almost exclusively for the structural steel components in the highway bridges in Ontario since 1968. This paper describes an investigation in 1981 of the performance of weathering steel bridges in the Province. Particular attention was paid to bridges situated where de-icing salts are used extensively in winter maintenance operations. Numerous examples of accelerated steel corrosion in weathering steel bridges were observed.

The paper concludes with some recommendations on how to minimize accelerated corrosion in weathering steel bridges.

Key Words: bridges, corrosion, de-icing chemicals, drainage, mill scale, salt

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ACCELERATED CORROSION IN WEATHERING STEEL BRIDGES

INTRODUCTION

The first use of weathering steel in North America was in a building constructed in 1963 in Moline, Illinois. Its first use in a highway bridge was also in the U.S., in 1964. Weathering steel was introduced into highway bridges in Ontario in 1967 and became the standard for structural steel components in bridges on the provincial highway system in 1968. In contrast to the introduction of most new materials and products, which follow a lengthy procedure of laboratory testing and field trials, there was a total commitment to the use of weathering steel. The reason for the rapid change was a simple one: the elimination of maintenance painting through the use of a slow rusting, unpainted steel (particularly a high strength weldable steel) was a major advance towards the goal of maintenance-free structures.

Over the next several years, there was little concern for the performance of weathering steel structures in Ontario except that a stable oxide film appeared to develop more slowly than anticipated and rust stains on piers and abutments were often unsightly. However a number of articles appearing in the literature around 1980 raised questions as to the general suitability of weathering steel in the highway environment. It was therefore decided to conduct a systematic investigation of conditions of weathering steel bridges in Ontario. Although the study was carried out in the winter of 1981, this paper includes a review of the literature published to the end of 1983.

Weathering Steel as a Material

Weathering steel is a low alloy steel containing up to three percent of alloying elements such as copper, chromium, nickel vanadium, phosphorus and silicon. It is also known as atmospheric corrosion resistant (ACR) steel and is marketed under the trade names of several steel companies. In Canada, the applicable material specification is CSA G40.21 Type A and in the United States, ASTM A588.

On exposure to the atmosphere and under suitable conditions, the corrosion rates of weathering steels are considerably less than ordinary mild steel in the same environment. As the steel weathers, it forms a rust which is light coloured, loose and fine grained. Further oxidation results in a tightly-adhering stable oxide film, or patina, which is rough, dark brown in colour (often with a purplish hue) and which inhibits further corrosion. The maximum thickness of the patina is 200 μm (1). The rapidity with which weathering steels develop a stable patina and its characteristic colour are determined largely by the atmospheric conditions of exposure. The time required has been quoted as generally more than 18 months but less than 3 years (2) to many years (3).

It is instructive to examine the conditions most favourable for the development of a stable patina. These are exposure to intermittent wetting and drying such as is provided by direct exposure to rain, wind and sun and the absence of corrosive pollutants, particularly salt. Weathering steel is not recommended for use in a marine environ-

ment where soluble chloride salt concentrations are significant (4) or for structures exposed to recurrent wetting by salt water (2). Experience has shown that the presence of salt prevents the formation of a stable oxide and corrosion proceeds unchecked. Except during construction, a large proportion of the steelwork in most highway bridges is sheltered from the direct action of rain and sun. Furthermore, parts of many structures are exposed to deicing salts either from vehicle spray or surface run-off through leaking expansion joints.

Rate of Corrosion of Weathering Steel

A number of studies have been carried out to measure the rate of corrosion of weathering steel. Many of the studies have included a comparison with other steels. A direct comparison with ordinary mild steel is difficult because the inclusion of scrap metal in the production of mild steel can result in differences in composition, and hence different corrosion performance. A typical figure is that weathering steel has an atmospheric corrosion resistance of approximately four times that of a plain carbon steel without copper. However, it is the actual corrosion rates which are of interest, rather than whether or not weathering steel performs well or badly in relation to a material which would not be used unprotected in an outdoor environment.

In the results of weathering tests which are summarized in Tables 1-4, the data has been changed from the format used in the original publications to allow a direct comparison between different studies.

Table 1 gives the results of the first five years of an eight year study, carried out in the United States to measure the corrosion rates of weathering steel at open exposure sites in different environments (5). It was found that the corrosion rate could be represented by the equation

$$C = At^B$$

where
C = corrosion loss
t = time
A = constant
B = constant

Constant A is determined primarily by the corrosivity of the environment and is a measure of the initial reactivity of the steel. Constant B is mainly influenced by the alloy content and reflects the long-term corrosion loss.

The better "steady-state" performance in the industrial atmospheres than in the rural environment was attributed to airborne dust becoming entrapped in the rust and increasing its protective nature by increasing the thickness of the barrier or decreasing its permeability.

Extensive measurements of the corrosion rate of weathering steels were undertaken in Czechoslovakia (1). The primary purpose was to study the effects of industrial pollution, particularly sulphur dioxide, using coupons installed at open exposure sites. The results

are summarized in Table 2. A range of values is given because many exposure sites and more than one type of weathering steel were included in the study. The performance of weathering steels in the microclimate of several industrial plants was also investigated. It was concluded that unprotected weathering steel is not suitable for use in atmospheres containing chlorine.

Table 3 presents the results of a study in the United Kingdom (3). The rate of corrosion measurements were also made on coupons at exposed sites. In addition to the tests reported in Table 3, corrosion rates were measured for periods up to 3 years on specimens placed underneath steel bridges. One bridge was a river crossing where the coupons were not exposed to deicing salts and the other two were bridges over freeways and exposed to vehicle spray. Although the corrosion rates decreased with time, after 3 years the rates of corrosion were 18 μm/year in the river crossing and 25 μm/year in the freeway bridges.

A more complete investigation of the effects of sheltering were included in another study in the United Kingdom (6). Coupons were installed in a sheltered area under various bridges and at adjacent open exposure sites. The results are given in Table 4. At the industrial and semi-rural sites, the bridge-sheltered corrosion rates were much lower than for the coupons in the open exposure. At the marine site the opposite was the case, possibly because of the washing action of rain at the open location. At the semi-rural location, the corrosion rate of coupons after five years was higher for the coupons beneath the bridge than for those in the open.

Although the results presented in Tables 1-4 represent weathering steels of different chemical composition exposed in widely different environments, the trends are similar and even the amount of corrosion after five years is comparable for the broad categories of environment used. In all cases, the corrosion rates decreased with time and achieved "steady state" conditions after three years in an open environment. However, at most of the sites, the corrosion rate could not be considered negligible. In the industrial environments, the initial rate of corrosion was highest but this diminished rapidly and, in one study, the "steady state" corrosion rate was lower in the industrial environment than the marine or rural environments.

The results in Table 4 emphasize the differences in performance between sheltered and open locations. In two of the three sites investigated, corrosion rates were higher in sheltered locations than for the open exposure sites. The data for the marine site, coupled with the data reported above for the freeway bridges, emphasize the adverse effects of chlorides on the corrosion of weathering steel under sheltered conditions.

Experience in Other Jurisdictions

A study undertaken by the Michigan Department of Transportation (7) in the late 1970's showed corrosion problems associated with the contamination of weathering steel bridges by deicing salts. Some design details which permitted crevice corrosion, galvanic corrosion or the accumulation of debris exhibited serious corrosion damage. In the most extreme case, hanger plates and pins with a cantilever expansion joint detail were found to require replacement after 14 years service. These findings led to a decision to impose a partial moratorium on the use of weathering steel in Michigan. The moratorium instituted May 2, 1979 (8) prohibited the use of unpainted steel in depressed roadway sections (where the most serious corrosion problems were observed) and in urban and industrial areas where heavy salting and industrial pollution created a corrosive environment. On February 6, 1980, the moratorium was made statewide (9). It was concluded that it was more cost-effective to paint A572 steel than to use unpainted A588 steel (10). In subsequent studies, it was found that although weathering steel bridges had a relatively good appearance at six to eight years of age, the data indicated that the same corrosion mechanisms were taking place as in many of the older structures. Concern was also expressed for the effect of pitting corrosion on the fatigue life of the structures (10) and a programme of maintenance painting was initiated.

Following the Michigan moratoria, a study was launched under the auspices of the American Iron and Steel Institute which included the examination of 49 weathering steel bridges in seven states (11). The study concluded that 30 percent of the bridges showed good performance in all areas, 58 percent showed good overall performance with moderate corrosion in some areas and 12 percent of the bridges showed good overall performance with heavy corrosion in some areas. The areas which exhibited moderate to heavy corrosion were found to be those most frequently subject to contact with salt-laden road run-off passing through leaking or open expansion joints. Other factors contributing to heavy corrosion were tunnel-like conditions which concentrate road spray on the structure, cracked concrete decks and direct run-off over the fascia beams. It was concluded that the majority of the weathering steel bridges were performing satisfactorily. There were some exceptions in Michigan where the corrosion was attributed to local conditions which included heavy salt usage, a tunnel environment and unusual design details.

The performance of weathering steel in highway bridges has also been investigated in Europe. The work carried out by the Transport and Road Research Laboratory (6) showed that corrosion rate measurements under open exposure site conditions were not generally applicable to steel in a highway bridge. In the sheltered environment beneath a bridge deck and in the presence of chlorides, corrosion rates were high and severe pitting corrosion developed. The effect of sheltering was found to have a greater effect on the colour and texture of rust than steel composition or geographic location. The uncertainty of corrosion rates in weathering steel bridges led the British Department of Transport to develop guidelines calling for the addition of 1 mm of steel to each exposed face in rural atmospheres and 2 mm in industrial atmospheres to allow for corrosion during the lifetime of the bridge (12). Department of Transport rules also prohibit the use

of unpainted weathering steel in freeway overpasses with standard overhead clearance because of the potential corrosion resulting from vehicle spray (13).

In 1978, the German Federal Ministry of Transportation also prohibited the use of weathering steel unless an exemption was specifically authorized (14). This decision was based upon experience of continuing corrosion because of persistent exposure to moisture and chemicals which led to the conclusion that even weathering steels require surface protection from the time of construction. Bolted or riveted connections which provide for capillary action and the trapping of moisture were identified as details particularly vulnerable to corrosion. An extensive ten year test programme was initiated which involves the measurement of corrosion rates on approximately 200 coupons at widely separated sites throughout Germany.

INSPECTION PROGRAMME

The complete change to the use of weathering steel by the Ministry in 1968 meant that, except for a few bridges included in contracts already awarded, all steel structures built since 1968 used weathering steel. Consequently, all weathering steel bridges could be identified from the Ministry's structure inventory. The inspection programme undertaken was not designed to constitute a random survey. Rather, the purpose was to examine those structures in the worst environmental conditions and compare their condition with structures in typical rural locations. In this way, it would be possible to gain an appreciation of the overall performance of weathering steel bridges in Ontario and to identify any specific problems which were developing. These objectives could be satisfied by an inspection of weathering steel bridges in Southern Ontario. At the time of the survey, there were 103 weathering steel bridges on the provincial highway system. Of these, 61 (or 60 percent) were examined, representing 80 percent of the weathering steel bridges located south of a line through Sudbury and North Bay. In addition, three municipal bridges were examined because of their potential to contribute useful data, either as a result of their age or the service environment.

The inspection programme involved a visual survey of each structure. Any defects or unusual features were recorded in note form and photographs. The condition of the interior of several box beam structures was investigated thoroughly. The survey was carried out during the winter of 1981. The winter months proved to be an excellent time to carry out such an investigation because those parts of the structures where salt accumulates could be readily identified.

The records of each inspection were too voluminous to reproduce in this paper. A summary of the investigation is given in Table 5, though, of necessity, some over-simplification is inevitable. Con-

sequently, it is more instructive to present the findings of the survey by discussion of some of the more interesting examples.

Site 37-156, Rouge River Bridge, Highway 7

The structure consists of I-section steel plate girders and was built in 1971. It is a river crossing located in a suburban area where salt usage is moderate to high. Figure 1 shows one end of one exterior girder which is stained with salt. The source of the salt is surface run-off, containing the rock salt used in winter maintenance operations, passing through a leaking expansion joint. Two observations are of particular interest. There is a large blister on the top of the bottom flange and a similar, but smaller, blister on the web stiffener. This flaky or laminar corrosion was found to be characteristic of the accelerated corrosion of weathering steel. When the flaky rust was removed, slight pitting corrosion was visible. The other feature of note is the presence of salt on the lower part of the web resulting from the capillary action of the oxide film. Corrosion damage was limited to approximately 2 m at each end of the girders. The remaining steelwork was in good condition.

Site 30-334, North Canal Bridge, Highway 400

The structure consists of rolled steel beams and is located on a freeway in a rural area where salt usage is high. It was built in 1950 and widened by the addition of weathering steel beams in 1971, at which time the original beams were repainted. The expansion joints at both abutments were leaking and this had caused extensive corrosion of the weathering steel beams and diaphragms. Figure 2 illustrates the underside of one of the interior weathering steel beams where a laminate of corrosion products had formed and extends as a single sheet over a length of approximately 2 m. Figure 3 shows an exterior beam of the same structure. The photograph shows the effects of surface run-off passing over the web and bottom flange of an I-section member and provides a good illustration of a phenomenon which was observed frequently in the course of the investigation. The bright oxide area of the web represents the steel remaining after separation of a corrosion laminate, the remains of which can be seen on the top of the bottom flange. As the corrosion products accumulate, moisture is retained on the top of the bottom flange and the corrosion is accelerated. Where this phenomenon occurs in welded girders, the weld become particularly vulnerable to corrosion. The capillary action of salt at the base of the web noted in Figure 1 is also visible in Figure 3.

Another interesting feature of this particular structure was that the top and bottom flanges of the interior beams which had been repainted were also corroding. While it is not possible to make a definitive statement about the relative performance of weathering and painted steel in the same environment because the quality of the repainting is uncertain, this particular site does indicate that any consideration of a return to painted steelwork should be taken cautiously.

Site 29-192 Bonnechere River Bridge, Highway 17N

The structure, of welded plate girder design, was built in 1974 and is located in a rural area where salt usage is light to moderate. The girders had weathered to a uniform dark appearance and were in good condition. Leakage of moisture and deicing salts through the joints was causing accelerated corrosion at the ends of the girders, especially on the exterior girders where thin laminations were visible on the top flanges and webs. Larger laminations were observed on the bottom of the bottom flanges. This is illustrated in Figure 4 in which a large corrosion-induced blister is visible.

Site 31-289 Scotch River Bridge, Highway 417

The structure consists of welded steel girders and is located in a rural area of moderate deicing salt usage. As in the previous examples, the overall condition of the steelwork was good except near the expansion joints. This particular structure is included in this report because one of the laminates was removed from the bottom flange of one of the girders and is illustrated in Figure 5. The thickness of the laminate varied between a single layer 1.5 mm thick and multiple layers totalling 3.1 mm thick. No attempt was made to relate this thickness to the loss of base metal section either by analysis of the corrosion products or measurement of the remaining thickness because of the substantial errors which may be introduced.

Site 19-471 Fanshawe Dam Bridge, Clarke Sideroad

This steel plate girder bridge is a municipal bridge which was included in the survey because it was the first weathering steel bridge in Ontario. The overall appearance and condition of the structure was good except for some unslightly rust stains on the piers as shown in Figure 6. The only areas of localized corrosion were found to be on the cross bracing and stiffeners in the areas of the expansion joints. This is illustrated in Figure 7. The joints on the bridge were finger joints which allow considerable surface run-off to come into contact with those parts of the structure adjacent to the joints.

Site 20-157 Big Otter Creek, Highway 3

This structure, of welded plate girder design, was built in 1972 and is shown in Figure 8. It is located in a rural area of heavy salt usage. The photograph illustrates the effect of moisture accumulation on the top of the bottom flange and the bottom of the web of an I-section girder, but is a more extreme example than shown in Figure 3. In this case, the structure is located in a sag curve such that the surface run-off flows downgrade towards the structure and through the expansion joint. Since the girders slope away from the joint, some of the moisture flows along the top of the bottom flange and capillary action brings salt into contact with the lower part of the web. As a result, approximately a 15 m length of the girder is susceptible to accelerated corrosion. A lesser amount of water flows on the underside of the top flange. The general case of this phenomenon is illustrated schematically in Figure 9 which shows how the

ends of a beam are affected by surface run-off and how the situation is aggravated for the case of structures located on a grade or in a sag curve.

Site 22-161 Rouge River Bridge, Highway 401

This structure, built in 1971, consists of box girders and is located on a freeway at the limits of an urban area where salt usage is high. The structure is located on a grade, the expansion joints leak and the steelwork is exposed to surface run-off as illustrated in Figure 9. Figure 10 illustrates the heavy salt-staining of the web of an interior girder and shows the recent separation of a corrosion lamina. Figure 11 depicts the bottom flange of the same girder illustrated in Figure 10. While there is no evidence of significant loss of section, the accelerated corrosion is of concern since the structure had only been in service for 10 years when the photograph was taken. There was no evidence of deterioration inside the box because of the presence of the solid concrete diagraphm which is visible in Figure 10.

Site 10-172 Sixteen Mile Creek Bridge, Highway 2

This box girder bridge was built in 1968 and represents the second oldest weathering steel bridge in Ontario. It is located in an urban municipality and heavily salted. The exterior of the girders has weathered to a uniform dark appearance which contributes to an attractive structure.

The most interesting aspect of this particular bridge is not its external appearance, but the conditions inside one of the exterior girders as illustrated in Figure 12. The photograph was taken approximately 4 m from the end of the girder looking towards the end diaphragm. A "tide-mark" on the diaphragm, webs and stiffeners shows that moisture has been present in the box and this has caused significant corrosion of the top surface of the bottom flange. Very large blisters cover the flange over an area extending approximately 3 m from the diaphragm. There was no evidence of leakage through the deck slab in this area and the means of access of the water is thought to be through the semi-circular holes around the anchor bolts. This hypothesis is supported by the fact that the corrosion is most advanced in the areas of the diaphragm immediately around the holes as shown in Figure 13. It is ironical that holes which were provided partly for drainage from the box allowed water to enter the box and cause such extensive corrosion. It is uncertain whether the source of the water was from the splash of run-off draining through the open finger joints on to the bearing seats or from high pressure hoses which were reported (but not confirmed) to have been used to clean the bearing seats. Accelerated corrosion was also observed at other locations. A diaphragm located at an intermediate pier at which there was a fixed, but leaking joint also showed accelerated corrosion damage as illustrated in Figure 14. Figure 15 illustrates the consequences of a poor design detail in which deck drainage pipes were carried through the side of the box. Leakage occurred around the pipe and caused significant corrosion of the web.

Site 36-232 Burlington Street Bridge

This large box girder structure was built in 1972 and is located on an urban arterial road subject to heavy salt usage. It is municipally owned and was included in the survey because of its location in a heavily industrialized area adjacent to a large steel plant. The exterior of the structure was in good condition, the only evidence of accelerated corrosion being adjacent to the expansion joints. Examination of the interior of some of the cells of the boxes showed them to be in excellent condition as illustrated in Figure 16. There was no evidence of moisture inside the boxes and the diaphragms were solid.

Site 14-348 Camlachie Sideroad, Highway 402

This box girder structure, built in 1974, is also of interest because of conditions inside one of the boxes. It is Ministry practice to place 25 mm drainage tubes in the corners of each bridge. These tubes prevent the ponding of water adjacent to the end dams during construction. After construction, they serve as weepholes for any moisture which seeps through the asphalt and collects on the top of the waterproofing membrane. Figure 17 represents a case of extremely poor detailing (and a failure to correct the error during construction) in which one of the tubes drains inside the box girder, thereby causing corrosion. The drainage tube appears in the top centre of the photograph. The diaphragm was also found to have small diameter holes which were flame cut and not shown on the drawings. These holes were presumably used to provide temporary support for forming the joint. At the time of inspection, the holes were permitting the seepage of moisture into the box.

Site 30-477, Highway 11 Overpass, Highway 400
Site 30-471, Simcoe Road 27, Highway 400

Site 30-477 is illustrated in Figure 18 and Site 30-471 in Figure 19. The structures were two and three years old respectively, at the time the photographs were taken and both illustrate the slow formation of the patina and the very uneven weathering which occurs when the steel is not blast cleaned. Figure 18 shows the effects of storage conditions of the steel plates prior to fabrication. Figure 19 illustrates a very blotchy appearance and the formation of a very loose oxide layer over parts of the surface while the mill scale remains intact in other areas.

DISCUSSION

The vast proportion of the steelwork in the structures investigated was found to be in good condition, though localized areas of accelerated corrosion were present on most structures. The study did, however, focus attention on situations in which weathering steel should not be used and identified the need to improve some design details. One striking feature of the investigation was the large proportion of the weathering steel structures located in rural areas. The infrequent usage of I-section girders in urban areas may well have contributed to the relatively few instances of serious defects noted.

After making a large number of observations in a survey of this type, it is possible to make a number of general statements with respect to those parts of weathering steel structures which are most susceptible to accelerated corrosion. Any surface or design detail which can trap moisture, dirt or debris is vulnerable. Such areas include:

i) Any steel components in the vicinity of leaking expansion joints.

ii) The top of the bottom flange of I-sections.

iii) The interior of any box section where moisture is present.

The majority of the instances of accelerated corrosion were associated with deck joints which were designed to be sealed but were leaking. This relationship has been found in other surveys. The fact that weathering steel corrodes rapidly in a moist, chloride-contaminated environment is to be expected and the product was not intended to be used under such service conditions. However, to adopt an approach that the weathering steel is performing well but the joints are at fault is simply unrealistic. It is inevitable that, given the current state-of-the-practice, a significant proportion of expansion joints will leak during their service life. Consequently, all structures need to be designed for this eventuality. A number of counter measures are possible including the provision of a continuous diaphragm of an inert material to prevent surface run-off contacting the superstructure or the selective application of a protective coating. Even where joints were leaking badly, there was evidence at a number of sites, of the benefits of good ventilation. Where there was a wide separation between the beams and the ballast wall, the severity of the corrosion was decreased. The Ontario Highway Bridge Design Code now requires a 200 mm gap at this location to reduce the effects of moisture-induced deterioration on both steel and concrete bridges.

It was noted several times in the course of the investigation that the top of the bottom flange and the weld between the web and bottom flange of I-section members are particularly vulnerable to corrosion. It is Ministry policy not to use I-sections in grade separations because of the possible accumulation of salt spray on the girders, especially in areas of heavy salting. Box sections are permissible in grade separations. An extreme example of the consequences of using I-sections is provided by the observations in Michigan (7). This situation draws attention to one of the most important issues surrounding the use of weathering steel. Since remedial action is neither desir-

able nor always effective; it is important to avoid those site, section geometry and design details which may result in poor performance.

One of the results of this and other studies is that it can no longer be assumed that the use of weathering steel will provide a maintenance-free life but simply avoids the need for first painting. Neither should it be assumed that weathering steel which is exhibiting accelerated corrosion can be protected by maintenance painting. Some difficulties exist in the cleaning and painting of weathering steel which is contaminated by chlorides and exhibiting pitting corrosion (7). The problems are complex and are currently the subject of research studies at the Steel Structures Painting Council and elsewhere.

All the box girders in the Ministry system have a deck which is waterproofed and paved. No evidence of leakage through cracks in the deck slab was found in any of the boxes inspected. However, any box girder bridge with an exposed concrete surface is vulnerable to corrosion inside the box, since the presence of moisture alone will cause corrosion and the situation will be aggravated if chlorides are also present.

The question of ventilation in box girder bridges is of considerable interest. In several of the bridges inspected, large accumulations of bird droppings and nesting material were present inside the box girders. The birds were found to be entering the boxes through holes no greater than 50 mm diameter in the intermediate pier diaphragms in simply supported structures. Evidence of vermin was found in a number of other box girder structures. In all cases, the holes into the boxes (usually around utility ducts) were small and the substantial amount of debris and nesting material appeared out of all proportion to the size of the access port. The potential problem with such debris is that if it becomes wet, then the lack of ventilation within the box provides an ideal environment for the accelerated corrosion of weathering steel even in the absence of chlorides.

The condition inside box beams which had a closed end diaphragm was significantly better than those with holes. The contrast between the conditions inside the box girders illustrated in Figures 12 and 16 is especially striking. Consequently, it is recommended that diaphragms be closed to keep out vermin and moisture and that ventilation be provided by means of a series of small holes in the bottom flange. A short tube should be inserted in each hole flush with the top surface of the bottom flange so that any seepage can escape without running on the underside of the structure. The tube should be fitted with a screen to prevent insects nesting in the box.

The provision of inspection hatches, while applicable to all box bridges, is worthy of comment. Although the inspection reported here was carried out with a bucket truck with a 10 m reach, many of the inspection hatches were inaccessible. The most common reasons were that the hatches were located directly over the roadway or over ground which would not support the inspection vehicle. At one location, where the hatch was located above the slope paving and about 3 m above ground, the hatch was open and there was evidence of a fire inside the box. Consequently, it is recommended that greater consideration be given to the location of hatches such that they are

accessible by inspection crews but not by unauthorized personnel. For structures in grade separations, the preferred location is directly above the shoulder of the highway.

It has been noted a number of times in this investigation that any ledge which can trap moisture increases the potential for accelerated corrosion. The welding detail between the webs and bottom flange of box girders has been the subject of some controversy. Current Ministry practice is to extend the flange as shown in the lower right of Figure 20. While there was no evidence of serious corrosion problems associated with this detail in the survey, the oldest box girders had been in service for only 13 years and it would seem prudent to avoid this ledge and detail the weld as shown in the upper right of Figure 20. This detail has been used successfully on a number of municipal structures. The extension of the web also affords the advantage of providing a drip check which reduces the possibility of the type of salt staining illustrated in Figure 11.

The appearance of the structures shown in Figures 18 and 19 supports the view that blast cleaning is required if it is necessary to promote even weathering for aesthetic reasons. The AISI inspection (11) concluded that, although there was some evidence of light pitting associated with mill scale, the mill scale will not adversely affect the corrosion performance of weathering steel but merely delays the formation of a stable patina. The report includes an example of the breakdown of mill scale over an eight year period during which time the mill scale was undercut and a normal patina developed. It has also been stated (10) that it is desirable to remove mill scale because it is cathodic to steel and hence a galvanic couple is established in the presence of moisture. This results in corrosion of the base metal at breaks in the mill scale and can result in pitting corrosion of the steel. Given the potential for pitting corrosion and the very long period involved in the formation of a stable oxide film under sheltered conditions, blast cleaning of the entire structure appears to be justified.

One of the key issues raised by the study reported here is the rate of corrosion of weathering steel in the highway environment, particularly the effect of moisture and chlorides on steel in a sheltered location. This issue has a significant impact at the design stage because of the economic implications of providing protective measures or increasing member thickness to allow for the corrosion which will occur during the life of the structures. In view of the need for additional information on rates of corrosion, the Ministry has recently initiated a research study to measure corrosion rates on coupons exposed in the bridge environment.

CONCLUSIONS

1. Most of the steelwork in weathering steel bridges is performing satisfactorily. However, there are localized areas of accelerated corrosion under moist, chloride-contaminated conditions.

2. More attention must be paid at the design stage to sites, section geometry and details which may result in poor performance.

3. Box girders with solid diaphragms are less susceptible to corrosion inside the girders than those with holes in the diaphragms.

4. Blast cleaning is necessary to obtain a uniform appearance and accelerate development of the patina.

5. More data is needed on the rate of corrosion of weathering steel under sheltered conditions in the highway environment.

RECOMMENDATIONS

The following recommendations apply specifically to highway bridges although similar principles apply to the use of weathering steel for other applications.

1. Pay particular attention to the service environment at sites where weathering steel is considered for use.

2. Avoid ledges and horizontal surfaces where moisture and debris can accumulate.

3. Provide for good ventilation of the superstructure.

4. Provide corrosion protection of weathering steel in the area of the expansion joints, either by controlling the flow path of run-off or the use of a protective coating.

5. Do not route drainage through closed sections.

6. Provide solid diaphragms in box girders and vents in the soffit.

7. Use the preferred weld detail indicated in Figure 20 for box girders.

8. Specify commercial blast cleaning of all steelwork.

9. Ensure that inspection hatches in box girders are accessible.

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9. Design Division Informational Memorandum #271-B, Michigan Dept. of Transportation, issued March 7, 1980.

10. Tinklenberg, G.L., "Corrosion of Unpainted Weathering Steel; Causes and Cure", Paper presented at the Second World Congress of Coating Systems for Bridges and Steel Structures, New York, New York, October 26-27, 1982.

11. AISI Task Group on Weathering Steel Bridges, "Performance of Weathering Steel in Highway Bridges - A First Phase Report", American Iron and Steel Institute, Washington, D.C. (1982).

12. Godfrey B., "Favourable Climate for Weathering Steel", NCE Supplement, Institution of Civil Engineers, London, August 1980.

13. Bishop R.R., and Winnett, M.A., "An Alternative to Bridge Painting", Report SR 621, Transport and Road Research Laboratory, Crowthrone, England (1980).

14. General Circular Memorandum, Highways Nr 3/1978, Bonn, April April 28, 1978.

Table 1: Corrosion Rates of ASTM A588 Grade B Steel Under Different Exposure Conditions (adapted from reference 5)

Site	Corrosion Rate, μm/year					Corrosion After 5 years μm
	Year 1	Year 2	Year 3	Year 4	Year 5	
marine	30	15	10	10	10	75
rural	30	10	10	5	5	60
industrial	45	10	5	5	4	69
industrial	35	10	5	4	3	57

Table 2: Effect of Pollution on Corrosion Rates (adapted from reference 1)

Pollution	Corrosion After 5 years μm	Steady-State Corrosion Rate* μm/year
low	35 to 50	2
moderate	50 to 70	3
heavy	130 to 175	23

* upper limit

Table 3: Corrosion Rates Under Differing Exposure Conditions (adapted from reference 3)

Site	Corrosion Rate, μm/year					Corrosion After 5 years, μm
	Year 1	Year 2	Year 3	Year 4	Year 5	
marine	52	34	14	14	14	128
rural	31	17	7	7	7	69
industrial	56	39	28	28	28	179
industrial	68	40	26	26	26	186

Table 4: Corrosion Rates Under Different Exposure Conditions (adapted from reference 6)

Site	Exposure	Corrosion Rate, μm/year					Corrosion After 5 years μm
		Year 1	Year 2	Year 3	Year 4	Year 5	
industrial	open	70	50	30	30	30	210
	sheltered	30	15	15	5	5	70
marine	open	45	15	15	10	10	95
	sheltered	35	30	30	30	30	155
semi-rural	open	50	20	20	10	10	110
	sheltered	20	15	15	15	15	80

Table 5: Summary of Bridge Inspections

Site No.	Year Built	Hwy	Girder Type	Crossing	Envir.	Joint Leakage	Comments
Ministry Structures							
37034	1971	400	I	canal	rural	heavy	heavy corrosion at beam ends
30334	1971	400	I	road	rural	heavy	heavy corrosion near joints
30317	1972	11	I	river	rural	slight	moderate corr'n at pier joints
37156	1971	7	I	river	suburban	heavy	heavy corrosion near joints
22161	1971	401	box	river	suburban	heavy	heavy corrosion near joints
22277	1973	401	I	road	suburban	none	good condition
10285	1978	403	box	road	suburban	none	patina slow to form
10286	1978	403	box	road	suburban	none	patina slow to form
10287	1978	403	box	road	suburban	none	patina slow to form
30128	1972	400	I	river	rural	heavy	heavy corrosion near joints
30469	1976	11	box	road	rural	none	good condition
30470	1976	11	box	road	rural	slight	slight corrosion inside one box
30471	1978	11	box	road	rural	none	very uneven weathering
30472	1978	11	box	road	rural	none	very uneven weathering
30473	1977	11	box	road	rural	none	very uneven weathering
30476	1979	11	box	road	rural	none	uneven weathering
30477	1979	11	box	road	rural	none	uneven weathering
42141	1969	11	I	lake	rural	heavy	heavy corrosion near joints
19522	1979	402	box	road	rural	none	good condition
19521	1978	402	box	road	rural	none	good condition
19520	1978	402	box	road	rural	none	good condition
19519	1977	402	box	road	rural	none	dark stains on columns
14361	1976	402	box	road	rural	none	uneven weathering
14356	1976	402	box	road	rural	none	corrosion near drainage tubes
14355	1976	402	box	road	rural	slight	uneven weathering
14354	1977	402	box	road	rural	none	good condition
14352	1976	402	I	road	rural	slight	moderate corrosion near joints
14351	1974	402	box	road	rural	moderate	debris and leakage inside boxes
14350	1974	402	box	road	rural	none	good condition
14349	1974	402	box	road	rural	moderate	moderate corrosion inside boxes
14348	1974	402	box	road	rural	none	drainage tube into west box
14347	1974	402	box	road	rural	moderate	uneven weathering
14346	1977	402	box	road	rural	moderate	slight corrosion near joints

Table 5: Summary of Bridge Inspections (cont'd)

Site No.	Year Built	Hwy	Girder Type	Crossing	Envir.	Joint Leakage	Comments
14340	1978	402	box	road	rural	moderate	heavy corrosion near joints
14339	1976	402	box	road	urban	heavy	heavy corrosion near joints
20157	1972	3	I	river	rural	heavy	heavy corrosion near joints
01147	1978	403	I	river	rural	none	good condition
30089	1976	400	I	rail	rural	none	corrosion near drainage tubes
42157	1974	11	I	river	rural	none	good condition
42079	1972	11	box	river	rural	slight	moderate corrosion near joints
42058	1974	11	I	river	rural	heavy	heavy corrosion near joints
44188	1976	11	I	river	rural	slight	slight corrosion near joints
44190	1976	11	I	road	rural	slight	slight corrosion near joints
44108	1975	522	I	river	rural	none	good condition
44033	1975	534	I	river	rural	none	good condition
46175	1976	64	box	lake	rural	slight	good condition
46124	1973	17	I	river	urban	moderate	heavy corrosion, no drip check
29196	1977	17	I	river	rural	slight	slight corrosion near joints
29055	1970	17	I	river	rural	moderate	moderate corrosion near joints
29192	1974	17	I	river	rural	heavy	heavy corrosion at beam ends
29129	1972	511	I	river	rural	moderate	moderate corrosion near joints
29128	1972	511	I	river	rural	moderate	moderate corrosion near joints
29191	1979	17	I	river	rural	moderate	slight corrosion near joints
30264	1973	16	box	river	rural	slight	moderate corrosion near joints
27210	1972	417	box	river	rural	heavy	heavy corrosion at beam ends
31289	1972	417	I	river	rural	heavy	heavy corrosion near joints
31288	1972	417	I	river	rural	moderate	heavy corrosion near joints
11280	1973	33	box	canal	rural	none	good condition
11145	1973	33	box	river	rural	none	corrosion near drainage tubes
371056	1979	400	I	road	urban	none	good condition
371061	1979	400	I	road	urban	none	corrosion near drainage tubes
Municipal Structures							
10172	1968	2	box	river	urban	heavy	heavy corrosion in S box
36232	1972	mun	box	road	urban	heavy	moderate corrosion at joints
19471	1967	mun	I	river	rural	heavy	heavy corrosion at joints

Figure 1/ Site 37-158, Rouge River Bridge, Highway 7
Exterior Girder

Figure 2/ Site 39-324, North Canal Bridge, Highway 450
Underside of Interior Weathering Steel Beam

Figure 3/ Site 30-344, North Canal Bridge, Highway 400
Exterior Beam

Figure 4/ Site 28-192, Bonnechere River Bridge, Highway 17N
Bottom Flange and Bearing Plate of Exterior Girder

Figure 5/ Site 31-289, Scotch River Bridge, Highway 417
Corrosion Products Removed from Bottom Flange

Figure 6/ Site 19-471, Fanshawe Dam Bridge, Clarke Sideroad

Figure 7/ Site 19-471, Fanshawe Dam Bridge, Clarke Sideroad
Cross Bracing Near Expansion Joint

Figure 8/ Site 20-157, Big Otter Creek, Highway 3
Exterior Girder

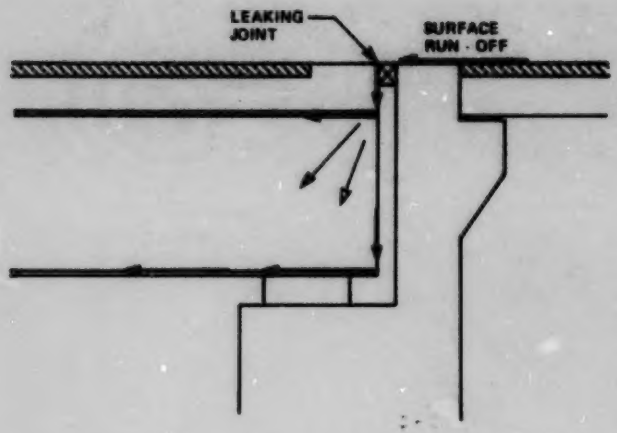

Figure 9/ Schematic Representation of the Flow of Surface Run-off at Leaking Joints

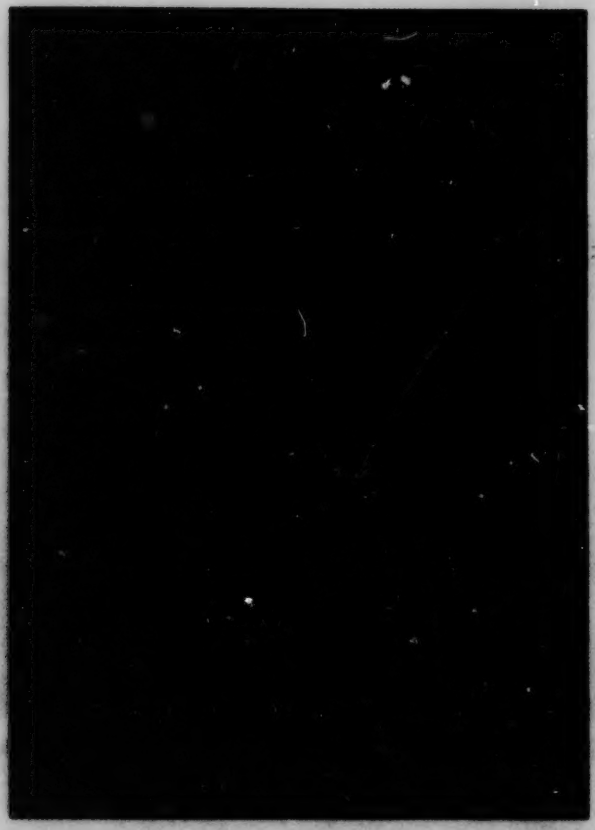

Figure 10/ Site 22-181, Rouge River Bridge, Highway 401 Web of Interior Girder

Figure 11/ Site 22-161, Rouge River Bridge, Highway 401
Flange of Interior Girder

Figure 12/ Site 10-172, Sixteen Mile Creek Bridge, Highway 2
Interior of Exterior Girder

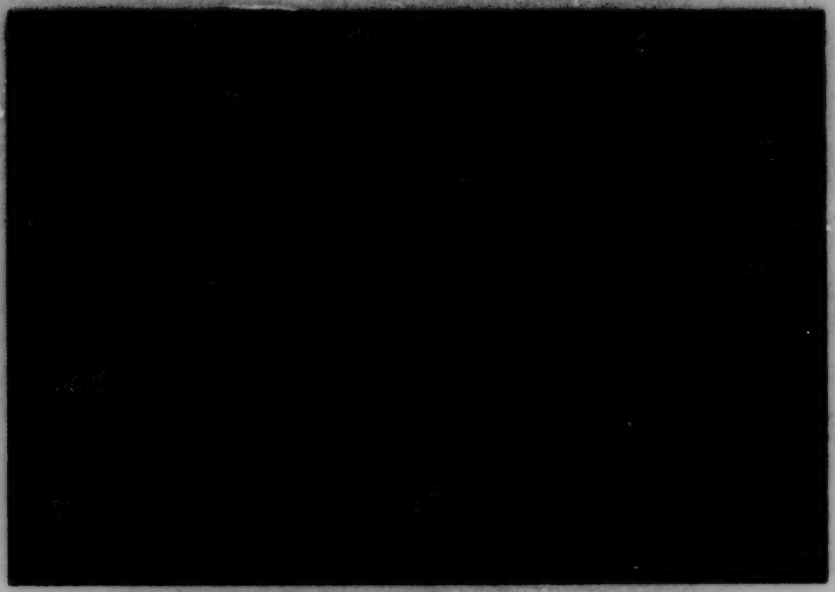

Figure 13/ Site 10-172, Sixteen Mile Creek Bridge, Highway 2
End Diaphragm

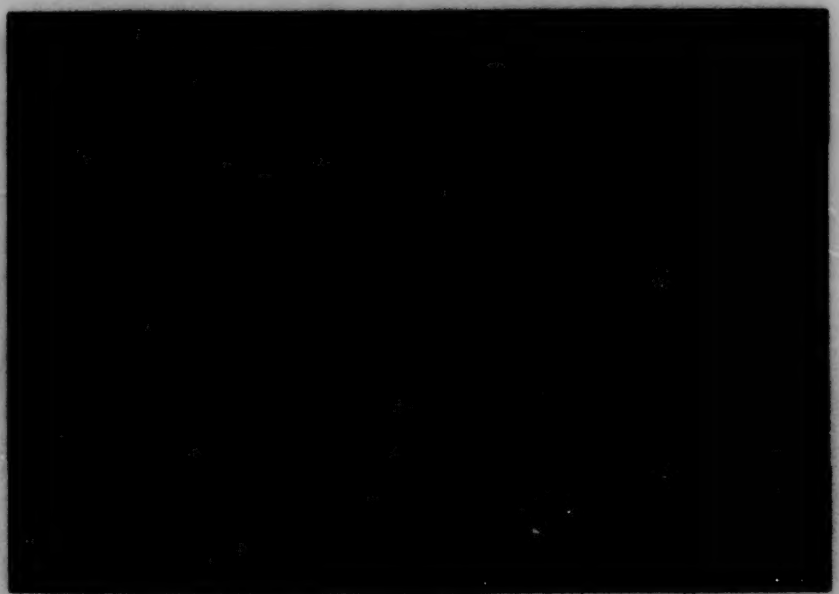

Figure 14/ Site 10-172, Sixteen Mile Creek Bridge, Highway 2
Intermediate Diaphragm

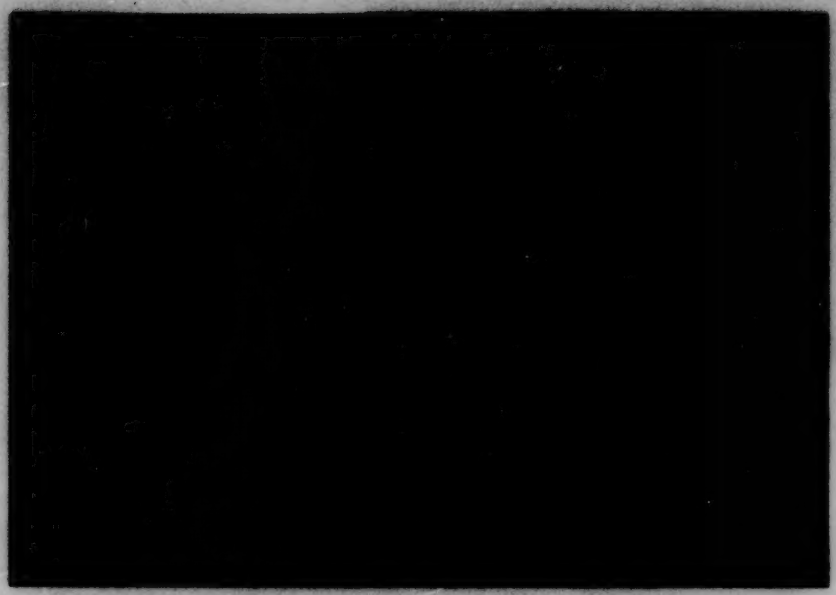

Figure 15/ Site 10-172, Sixteen Mile Creek Bridge, Highway 2
Drainage Pipe through Exterior Girder

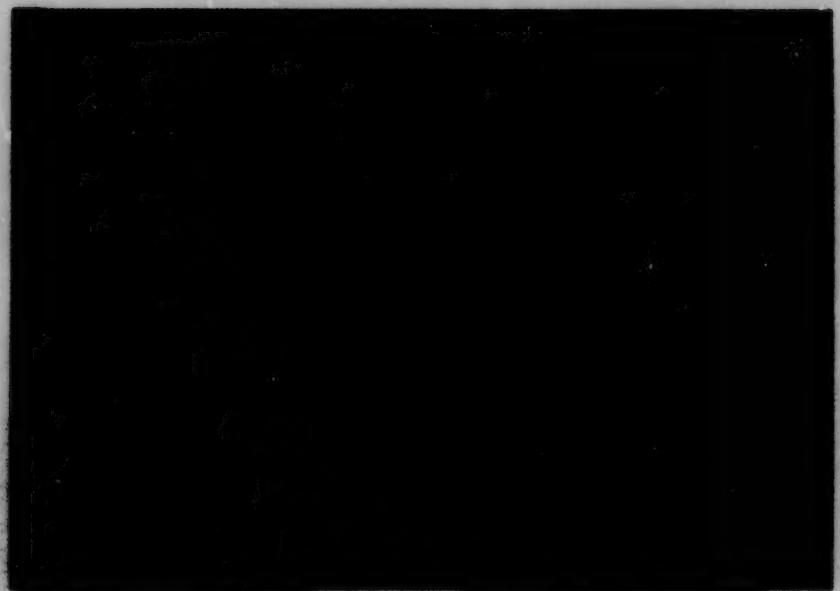

Figure 16/ Site 35-[illegible] Bridge
Interior [illegible] Girder

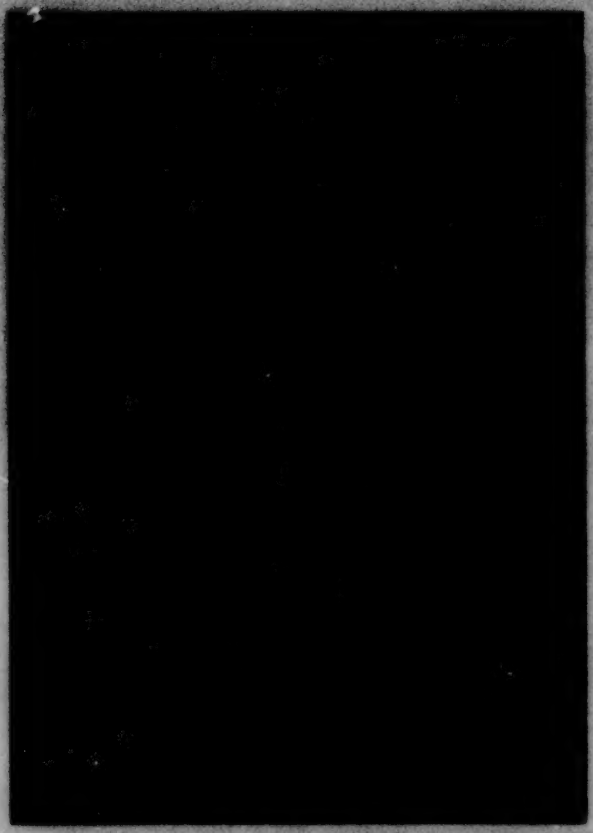

Figure 17/ Site 14-348, Carnlashie Sideroad, Highway 402
Interior of Exterior Girder

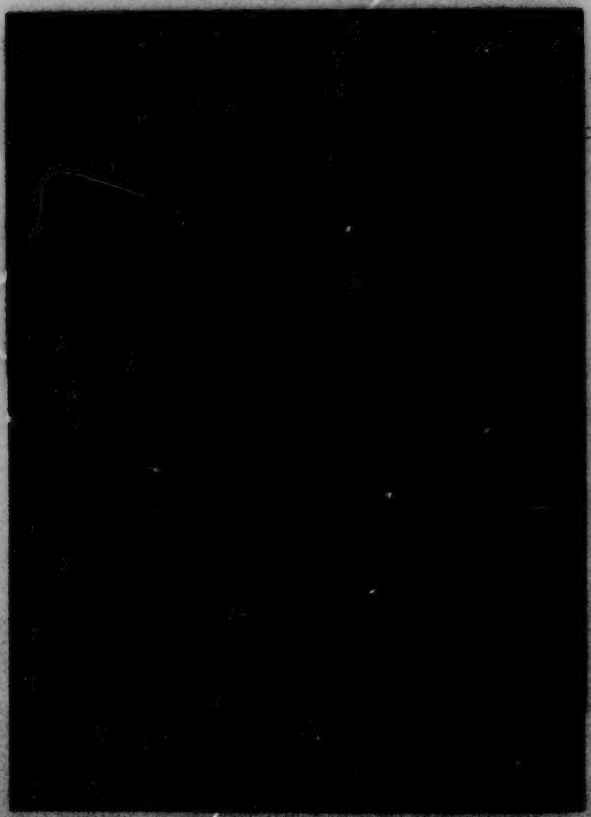

Figure 18/ Site 50-[illegible], Highway 11 Overpass, Highway 400

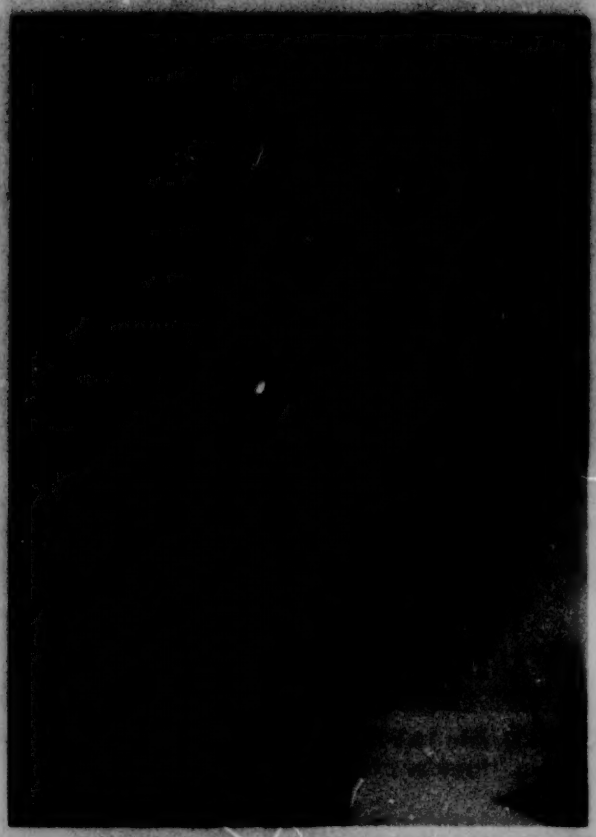

Figure 18/ Site 89-471, Simcoe Road 27, Highway 400
Undesirable View

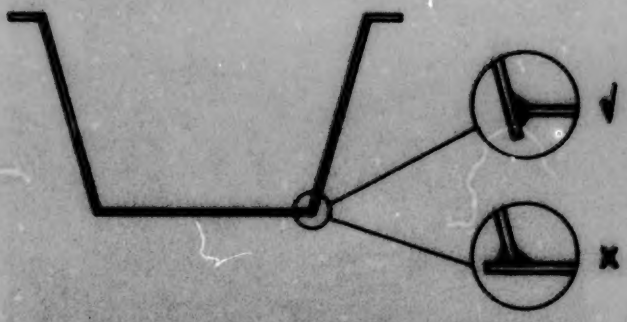

Figure 20/ Preferred Weld Detail for Box Girder